Critical decline of earthworms from organic origins under intensive, SOM-depleting agriculture

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Abstract

In view of recent reports of critical declines of microbes, plants, insects and other invertebrates, birds and other vertebrates, the situation pertaining to neglected earthworms was investigated. The insect reports found the probable cause of general loss was lack of recruitment from agricultural fields (except for pest species). Earthworm decline under agricultural intensification compared to organic husbandry is herein charted from several long-term agronomic trials, some operational >175 years. Relative losses of 60-100% (average - 83.8%) match or exceed those reported for other faunal groups. Thus earthworms are conclusively shown to be similarly depleted from their optima in agrichemical fields. These preliminary findings are indicative rather than definitive but, rather than awaiting prolonged study, highlight an urgent need for innovative agro-ecological responses by concerned parties. Non-chemical, organic management reduces topsoil/SOM erosion and degradation, conserves soil fauna and produces equivalent or higher crop and pasture yields at lower cost. Decline of essential soil fauna adds weight for rational re-evaluation of organic husbandry as a viable means for food production and environmental conservation, hence various combined benefits in terms of yields, soil restoration, biodiversity and economics are briefly discussed. Persistence with failing chemical agriculture neither makes ecological nor economic sense.

Keywords: Megadrile earthworms, soil-fauna surveys, biodiversity loss, agro-ecology, humus.

Introduction

In 2017 a startling study from Germany reported around 80 percent decline of total flying insect biomass in just 27 years (1989-2014) from protected nature reserves [1]. The authors attributed the plausible cause of this major and hitherto unrecognized loss of insects to "*agricultural intensification*" in surrounding areas. They noted few similar studies citing but one previous report from Rothamsted Insect Survey (RIS) that plotted a decline over a 30 year period (1973-2002) in one of four UK sites [2]. This prior UK report noted that this survey coincided with rapid agricultural intensification from the 1950s and suspected that three stable sites – having much lower biomass and this mainly of insect pest species – had already collapsed before monitoring commenced in the 1970s. This situation is characteristic of a broader and critical extinction issue [3-4]. Authors of a global review (Rockström et al. 2009) [5] identified both "*rate of biodiversity loss*" and synthetic fertilizer overuse as the most severe and pressing of global problems, solutions for which they suggest as a 25% reduction in N fertilizers and: "*Agricultural systems that better mimic natural processes (e.g., complex agro-ecosystems)*". A good measure of proper ecological functioning of such systems is past and current status of soil fauna, in particular earthworms (Oligochaeta : Megadrilacea) – the subjects of this report – that both monitor and mediate natural soil processes.

While comprehensive summaries of earthworm ecology, their role in humus formation (= SOM, soil organic matter), and absolute population values are available [6-8], comparative information is quite limited such that a recent meta-analysis of soil biodiversity [9] entirely excluded earthworms "*due to small sample sizes (*n *< 5).*"

The present report is a quantitative re-analysis of the scant historical data on earthworm biomass from long-term studies in an attempt to derive similar starting references as in the two insect biomass reports. However, earthworm survey results often differ considerably depending upon soil, season or sampling method, thus relative or relational findings are required. In lieu of consistent historical records, comparative sites that have not undergone extreme agricultural intensification are sought to provide de facto control metrics. Irregular earthworm surveys have been conducted at Sir John Lawes' Rothamsted Research Station, the earliest established and longest running facility to test agronomic effects of agricultural chemicals, with various levels of controls, during its 175 year operation since 1843. Reports of

soil faunal surveys at Rothamsted conducted between 1921 and 2014 are available [10-14]. Another set of earthworm data [15-17] of intensified versus non-intensified soil management is from Lady Eve Balfour's Haughley Experiment that ran for more than forty years from 1939 to 1984 [18-19]. Other comparable earthworm data is from the Swiss FiBL DOK agronomic field trials that have been operational for almost forty years, since 1978, on land that, as for parts of the other two sites, was originally pasture grassland [20-21].

The *a priori* assumption in the current study is that the non-intensified plots or sections of these facilities would support an earthworm fauna not dissimilar in composition and scale to those present prior to agrichemical intensification. The chemical fields and plots typically represent the contemporary situation. Rothamsted estate and Haughley farm are thought to have heritage from Roman times (about two millennia ago) or subsequent Anglo-Saxon settlement (about 1,000 years ago), respectively. To forestall the obvious argument that Rothamsted plots with nil fertilizers are a better control check, it is certain that no current nor historic farmer would consider such an unproductive management regime. However, zero fertilizer data, where available, are included for the sake of thoroughness.

Rothamsted's Broadbalk arable and Park Grass pasture experiments – begun in 1843 and 1856, respectively – are the world's oldest operational ecological experiments; before this Broadbalk is thought to have been in arable cropping since at least 1623 and Park Grass similarly under pasture for many centuries [22]. Regarding statistical reliability of long-term studies, it is unrealistic and impractical to wholly replicate such unique sites as chemical Rothamsted or organic Haughley without large investment in time and funds, nevertheless their insightful findings are proving to be most useful scientific indicators [23-24].

Estimated numbers of earthworms per hectare in the soils of the Rothamsted Experimental Station were given by Balfour (1947) [25] as roughly 21 million in grassland, 16.8 million in farm-yard manured land (-20% lower) and 1.2 million in unmanured land (-93% lower again), but she also noted that both earthworms and fungi appear to be highly sensitive to sulphate of ammonia fertilizer. Her information (numbers per acre) was seemingly based upon studies by earlier workers [6, 10-11]. A 1926 survey [11] already recorded drastic decline of all soil fauna by up to -98.9% at Rothamsted after just 50 years of synthetic fertilizer use, requiring management reversions to traditional methods (e.g. liming and crop rotations). The present

analysis reasonably compares historical earthworm studies to most recent surveys from the same and from similar sites and concludes that, as with the insects, they too are in jeopardy.

Methods

For insects, both historical and recent Rothamsted RIS data [2] quoted by the German study [1] are normalized (untransformed) for better comparison with the latest German findings.

Earthworm data from field surveys by various authors are re-analysed as comparative data for intensified (i.e., synthetic agrichemical) versus non-intensified (i.e., organic) farm soils. Rothamsted surveys are of the Broadbalk, Park Grass and Barn Field long-term trial sites [22]. From 1939, Haughley farm was divided into three (with approval of Rothamsted researchers) comprising self-contained organic, mixed and non-organic sections [16, 18]. The Swiss DOK trial has several treatment combinations, but for comparison to these other two experiments, only their data from Organic, Mixed and Conventional wheat crops [20-21] are considered.

The premise for surveys is that, firstly, the organically fertilized plots best preserve the soil situation more typical of the prevailing management before agricultural intensification and thus preserve the probable starting condition of earthworm (and other invertebrate) populations from earlier times. For instance, the continuous organically fertilized Broadbalk arable and Park Grass pasture sites that are thought to have been so for prior centuries at Rothamsted, as for the "Saxon" permanent pasture at Haughley, best represent the antecedent state prior to synthetic fertilization and/or cultivation. Secondly, any crop, soil, plant or soil biota changes are reasonably assumed to be due to the cumulative agronomic management effects. Thirdly, any geological, seasonal or sampling variables are nullified by simultaneity and sympatric proximity.

Whereas most other reports give misconstrued values as open-ended percentage increases from the lowest biodiversity and yield data, the present study – possibly uniquely – measures relative changes from the assumed optimal starting points giving the statistical percentage change (often decreases) rather than percentage difference. The formula used is:

$((y2 - y1) / y1)*100$ = percentage change (%), where y1 is original and y2 is final value.

As tropical organic reports are particularly scarce, a recent Philippines earthworm study on organic paddy rice and broad-acre sugarcane is included [17] for comparison.

Throughout, FYM is Farm-Yard-Manure (a coarse compost), N-P-K are chemical fertilizers, and SOM (Soil-Organic-Matter = humus) that from a vanBemmelen factor is ~58% carbon (SOC).

Results

Insect data

RIS findings from the UK, when untransformed to approximate absolute values to comply with German results as these were originally presented, show similar decline rates (Fig 1).

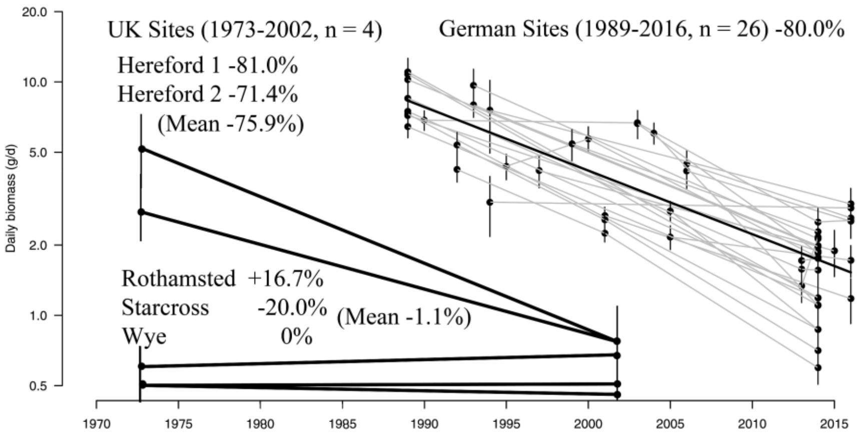

Figure 1. UK high-flying insect biomass (g/day) untransformed to comply with German malaise trap data (approximate 95% confidence intervals added from original scales).

Invertebrate data

Search of Rothamsted e-RA website (http://www.era.rothamsted.ac.uk/) provides only three records for comprehensive soil invertebrate surveys [10-12] which are herein evaluated (Fig 2).

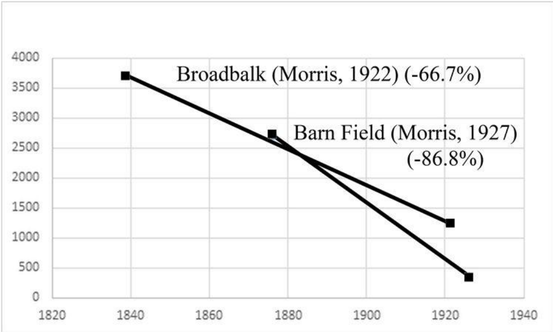

Figure 2. Plot of Rothamsted total soil invertebrates (mean numbers m^{-2}, biomass unavailable) for Broadbalk FYM vs. Nil fertilizer [10]; and for Barn Field FYM vs. no FYM (i.e., combined mineral fertilizer and nil fertilizer data) [11].

In both cases for data in Fig 2, the FYM plots are here taken to represent or preserve the original state at inception. A later survey for Park Grass [12] is incomplete and incomparable with its total counts seemingly miscalculated by a factor of two, and data seeming to counter-indicate overall invertebrate decrease trend for Nil fertilizer vs. FYM plots of earlier surveys, possibly because any zero results, as were found earlier [10-11], were excluded.

Earthworm data

Rothamsted, UK

Layout designs and findings from the various long-term experiments are available [22, 26]. Results of earthworm surveys [10-14] at Rothamsted are presented in Tables 1-5.

Table 1. Broadbalk earthworms, Spring 2014 at 170 yrs (Sizmur *et al.* 2017: fig. 2, tabs. A1-2) [14].

Treatment (plot)*	Abundance m^{-2} (% change)	Biomass gm^{-2} (% change)
Mean FYM (plot 2.1; n = 2)	400.00 (0%)	108.90 (0%)
Mean N (plot 8; n = 2)	70.35 (-82.4%)	6.05 (-94.4%)

*Sample plots are 2.1 and 8 in sections 0 (straw) and 1 (no straw) (T. Sizmur pers. comm.). Note although FYM in 2.1 was applied from 1885, not 1843 as in plot 2.2, it is assumed to have returned to its original 1843 state. Later plot 2.1 FYM was augmented with synthetic N (at 2N or a rate of 96 kg N ha^{-1} after 1968, raised to 3N or 144 kg N ha^{-1} after 2005).

Table 2. Broadbalk (wheat) earthworm survey in 1979 after 135 yrs (Edwards & Lofty 1982: tab. 2 – note these data differ considerably from their figs. 1b, 2-3 values) [13].

	Abundance m^{-2} (% change)	**Biomass gm^{-2} (% change)**
FYM (plots 2.1, 2.2; n = 2)*	(94.2 + 89.4)/2= 91.8 (0%)	(71 + 44)/2 = 57.1 (0%)
4N (plot 9, n = 4)	42.9 (-53.3%)	25.9 (-54.6%)
3N (plot 8, n = 4)*	30.6 (-66.7%)	13.7 (-76.0%)
2N (plot 7, n = 4)	20.9 (-77.2%)	6.2 (-89.1%)
1N (plot 6, n = 4)	10.0 (-89.1%)	4.7(-91.8%)
Mean of all four N plots	26.1 (-71.6%)	12.6(-77.9%)
Nil fertilizers (plots 5,3; n = 2)*	(7.5 + 5.6)/2 = 6.5 (-92.9%)	(8.9+2.7)/2 = 5.8 (-89.8%)

* Combining of FYM plot data is justified by 2-way ANOVA showing no significant difference (p = 0.619); plots 2.1 and 8 were also surveyed by Sizmur et al. (2017) [14].

Table 3. Rothamsted's Park Grass (pasture) in 1973 and 1974 survey after 118 yrs, recalculated from original data (in Edwards & Lofty 1975: tab. 4) [12] that differs somewhat from the same (correct?) data proffered in Edwards & Lofty (1982: tab.4) [13].

	Abundance m^{-2} (% change)	**Biomass gm^{-2} (% change)**
FYM Plot 13 (n = 4)*	55.0 (0%)	66.9 (0%)
Nil fertilizer Plots 2, 3, 12 (n = 8)	37.9 (-31.1%)	43.1 (-43.16%)
NPK Plots 14, 16 (n = 4)	17.3 (-68.6%)	21.8 (-67.5%)

*FYM at 35 t ha^{-1} was generally applied every fourth year, supplemented with fishmeal.

Data in Tables 1-3 show FYM plots had much higher earthworms; and Edwards & Lofty (1975: fig. 7) [12] plotted an earthworm abundance inversely proportional to the synthetic nitrogen rates, which was opposite to their subsequent Edwards & Lofty (1982: fig. 2) [13] Broadbalk synthetics result where abundance was inversely proportional to N (but not significantly).

In 1975 it was noted [12] that in other NPK treatments (Park Grass plots 9-11) the earthworms were completely eliminated by pH <4.0 but mean abundance and biomass (n = 16) were 23.5 m^{-2} and 20 gm^{-2} i.e., -57% and -70% compared to the FYM plot totals. Edwards & Lofty (1982: tab. 4) [13] have the same Park Grass data somewhat differently presented (here recalculated as 54.1 m^{-2} and 64.9 g m^{-2} for FYM and 47.1 m^{-2} and 44.2 g m^{-2} for nil fertilizer plots that would be different by just -36.3% and -46.6%). Misdating the start of the 1856 experiment as 1836 or

1843, their subsequent paper further misconstrues earthworm populations as raised by 11% on adding FYM compared to nil fertilizer and entirely omits the NPK plot data – see Discussion.

Rothamsted's Barn Field experiment on mangel-wurzels (mainly turnips) ran from 1876-1959, but the land had similar fertilizers for other root crops since 1856 and was originally started in 1843. Earthworm survey [13, 11] are recalculated as summarized in Tables 4-5.

Table 4. Rothamsted's 1843 Barn Field (root crops), "1959" earthworm survey, i.e., >116 years (recalculated from Edwards & Lofty 1982: tab. 3) [13].

Treatment (and plots?)	Abundance m^{-2} (%)	Biomass gm^{-2} (% change)
FYM (n = 1, O1)	78.7 (0%)	43.7 (0%)
FYM + 2N (NH4) (A1+?)	76.8 (-2.4%)	46.4 (6.2%)
FYM + 2N (NaNO3) (O2?)	35.8 (-54.5%)	17.1 (-60.9%)
2N + superphosphate	28.9 (-63.3%)	19.2 (-56.1%)
Mean all 3 synthetic plots	47.2 (-40.1%)	27.6 (-36.9%)
Nil fertilizer (n = 1)	10.6 (-86.5%)	6.9 (-84.2%)

Actual plot codes were not provided and it is possible that plots with zero worms were excluded (cf. Table 5 data for Barn Field plot O5).

Table 5. Earthworm survey summary from Barn Field during 1923-1926, i.e. >50 years under mangolds since 1876, (recalculated from Morris 1927: tab. 1) [11].

Treatment – Plot	Abundance m^{-2} (%)
FYM – O1	237.2 (0%)
FYM + NH4 salts – A1	153.2 (-35.4%)
FYM + PK – O2	137.9 (-41.9%)
Superphosphate – O5	0 (-100%)
Ammonium salts – A8	3.7 (-98.4%)
Mean of both synthetic plots	1.9 (-98.9%)
Nil fertilizer - O8	5.7 (-97.6%)

These data in Table 5 are of abundance (but no biomass data available) for Megadrile earthworms ("Terricolae"); however, in FYM plots, over 50% of all invertebrates were worms that included Nematodes, Microdriles and Megadriles. Total of all invertebrate counts in FYM

plots was 2,711 m^{-2} compared to just 358.5 m^{-2} in "undunged" plots (Morris, 1927: tab. 1) [11], i.e., a severe total invertebrates decline of -86.8%.

Haughley, UK

Earthworm surveys at Haughley in 1980-1981, i.e., after 35-40 yrs (from 1939 or 1945) [15-17], from winter wheat crops at equivalent stages of cultivation in all three sections are given in Table 6. Note that Haughley started in 1939 but Balfour (1947/8) [25] has the non-chemical fields still under pasture in 1945, thus the trial period is a bit less and likely about 35 years.

Table 6. Summary of Haughley earthworm surveys [15-17] with comparative % changes.

	Abundance m^{-2} (% change)	**Biomass gm^{-2} (% change)**
Organic Permanent Pasture	424.0^{a} (+137.4)	117.6^{d} (+77.6%)
Organic (wheat)	178.6^{b} (0%)	66.2^{e} (0%)
Mixed (wheat)	97.5^{c} (-45.4%)	35.4^{f} (-46.5%)
Stockless/Chemical (wheat)	100.0^{c} (-44.0%)	34.7^{f} (-47.6%)

Mean values with different superscripts differ significantly ($p < 0.05$) from ANOVA.

Swiss DOK field trials

Earthworm data (Pfiffner& Mäder, 1997: figs. 1-2; tab. 3) [20] from 1978-1991, i.e., after 13 yrs, for wheat only to allow comparison with the Broadbalk and Haughley trials, is given in Table 7.

T**able 7. Swiss DOK earthworm data from (Pfiffner& Mäder, 1997: figs. 1-2; tab. 3) [20]**.

Treatment	**No. m^{-2}**	**% change**	**g m^{-2}**	**% change**
Organic	350.0^{a}	0.0	300.0^{a}	0.0
Conventional (Mixed)	120.0^{b}	-65.7	100.0^{b}	-66.7
Mineral (Chemical)	100.0^{b}	-71.4	98.0^{b}	-67.3
Means		-68.6		-67.0

Means with different superscript letters differ significantly ($p < 0.05$). Note that other crops had much higher values (up to 650 worms m^{-2} after beetroot and 400 g m^{-2} after

potatoes). Later DOK non-organic wheat plots were found with about -60% lower earthworm abundance (no biomass data) after 27 years (1978-2005) (Birkhofer 2008) [21].

Earthworm data from the above tables and from the Philippine experiments are in Table 8.

Table 8. Earthworm summary of optimal/historic (organic) values and % change of actual values from simultaneous, on-site, agrichemical surveys, with duration (yrs) of regime.

Years	No. m-^{2} (%)	Biomass gm-^{2} (%)	Locality/Report
5	36.0 (-36.1)	13.8 (-97.1)	Filipino PI rice (Blakemore 2016a) [17]
10	44.3 (-54.9)	-	Filipino PI sugar (Blakemore 2016a) [17]
13	350 (-65.7)	300 (-66.7)	FiBL DOK wheat Mix (Pfiffner/Mäder 1997) [20]
13	350 (-71.4)	300 (-67.3)	FiBL DOK wheat Chem (Pfiffner/Mäder 1997) [20]
27	148 (-59.5)	-	DOK (Birkhofer 2008) [21]
35	179.6 (-45.4)	66.2 (-46.5)	Haughley wheat Mix (Blakemore 2000) [16]
35	179.6 (-44.0)	66.2 (-47.6)	Haughley wheat Chem (Blakemore 2000) [16]
50	175.9 (-98.2)	-	Roth BF (Morris 1927) [11]
80	250 (-54.4)	-	Roth BB (Morris 1922) [10]
116	78.7 (-40.1)	43.7 (-36.9)	Roth BF (E & L 1982) [13]
135	91.8 (-71.6)	57.1 (-77.8)	Roth BB (E & L 1982) [13]
143	55.0 (-68.6)	66.9 (-67.5)	Roth PG (E & L 1975) [12]
170	400 (-82.4)	108.9 (-94.4)	Roth BB (Sizmur 2017) [14]
MEANS	179.9 (-60.9%)	113.6 (-66.9%)	

PI – Philippines; Mix – mixed organic/chemical, Chem – agrichemical only; Roth – Rothamsted (BB – Broadbalk grain, BF – Barn Field roots, PG – Park Grass pasture). Most of the original matched pairs differed significantly in original reports. The greatest changes are -98.2 % for abundance (Rothamsted roots) and -97.1 % for biomass (Filipino PI rice).

Assumed rates of earthworm biomass changes for Rothamsted and Haughley are plotted (Fig 3) (PI and DOK data are for shorter durations and are too heteroscedastic for inclusion).

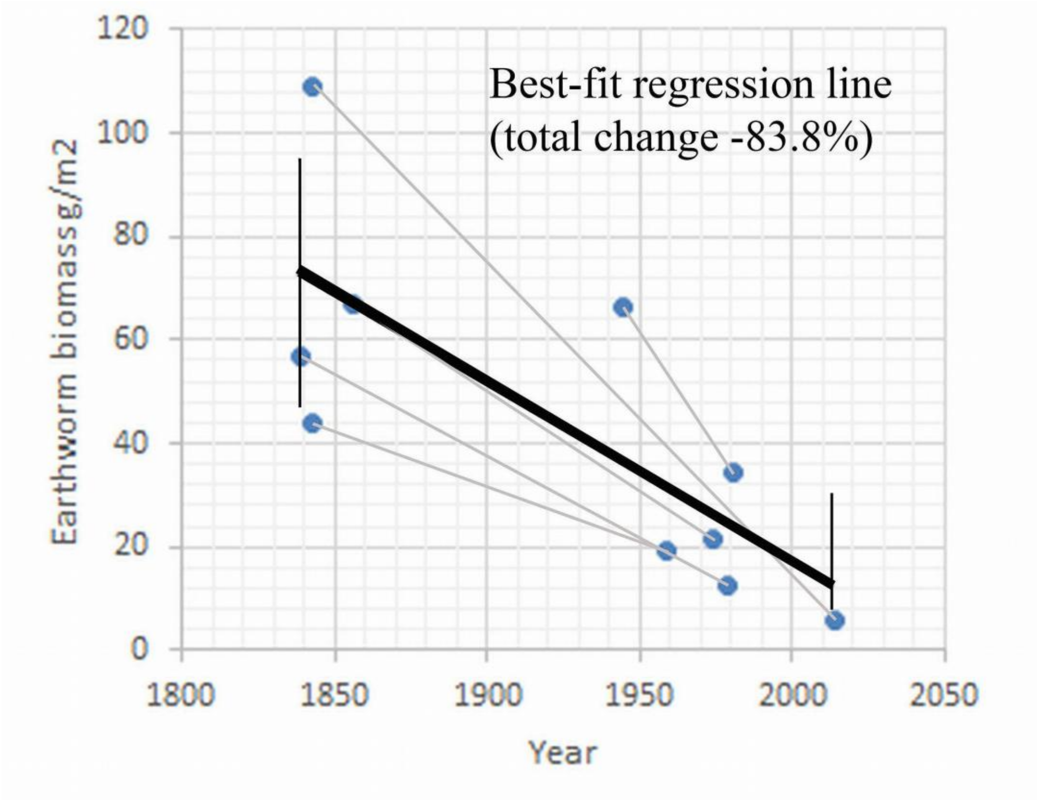

Figure 3. Comparative earthworm biomass (g/m^2) plotted against experimental period [means = 68.6 ± 24.4 vs. 18.9 ± 10.8 (-72.5%), ANOVA p=0.003, i.e., decline highly significant].

A best-fit regression line analysis (Fig 3) is also significant (r^2 = 0.577, p = 0.011), i.e, biomass decline by (-83.8%) is with agrichemical duration, even though initial loss rates may have been higher at implementation. It is assumed that earthworm populations under FYM or other long-term organic treatment will have been stable since inception, thus represent antecedent or historical states, compared to contemporary values for agrichemical intensifications at each site. In no case was earthworm biomass found to be increased by agricultural intensification.

Soil characteristics relating to earthworm activity

Relevant soil data for Rothamsted's Broadbalk and Haughley are presented in Tables 9-10.

Table 9. Broadbalk soil samples (2005) plus microbes and Cadmium accumulation in crops.

	Moisture % (% change)	BD (g cm^{-3})	pH	SOC % (% change)	Microbes	Cd in grain (mg/kg)*
Woodland	41 (28%)	0.9	7.70	3.45 (22%)	Highest	-
FYM (plot 2.2)	32 (0%)	1.1	7.82	2.83 (0%)	Higher	40-46
N288 (plot 16)	25 (-22%)	1.2	7.80	1.2 (-58%)	Reduced	-
N144 (plot 08)	27 (-16%)	1.2	7.30	1.13 (-60%)	Reduced	71-83
N0 (plot 05)	25 (-22%)	1.2	8.10	0.9 (-68%)	Reduced	-

BD – Bulk density; SOC – soil organic carbon (= humus). Soil data from Clark et al. (2012: tab. 1) [27]; Cd in grain harvests between 1877-1984 [28] and from Jones & Johnston (1989: fig. 2) [29]. Note: Plots 2.2 and 8 were surveyed either by Sizmur et al. (2016) [14] or Edwards & Lofty (1982) [13]. Note that regenerated woodland had much higher moisture and SOC.

Rothamsted Research (2012: pg 15) [22] reports that microbial biomass of the FYM plots is approximately twice that of the plots given either NPK or no fertilizers – actually what they show is depletion of microbes by ~-50% with synthetics. Other soil data can be found on their website (http://www.era.rothamsted.ac.uk/) and in diverse published reports.

Table 10. Haughley soil characteristics from Blakemore (2000) [16] at time of survey.

	H_2O % (%)	BD (g cm^{-3}) (%)	pH	SOC % (%)
Perm. Pasture	42.0 (+35.5%)	0.9 (+12.5%)	7.5	9.9* (+148%)
Organic (wheat)	31.0 (0%)	0.8 (0%)	7.2	4.0 (0%)
Mixed (wheat)	24.0 (-22.6%)	0.8 (0%)	7.6	2.3 (-41.5%)
Stockless (wheat)	22.0 (-29.0%)	1.1 (+37.5%)	7.5	1.8 (-56.3%)

*Pasture SOC estimated from its SOM (= humus). BD – Bulk density; SOC – soil organic carbon; Stockless is agrichemical. Note that permanent pasture had much higher moisture and SOC.

Crop yields and economic return

Crop yields are highly variable: For Rothamsted's Broadbalk and the Haughley study sites these are presented in Tables 11-13, other yield data is quoted from various sources as cited.

Table 11. Broadbalk initial yield wheat in 1844 (after Addiscott 2005: tab. 1.1) [30].

	Grain (t ha^{-1})	Straw (t ha^{-1})	Total	% change
Nil	1,030	1,256	2,286	-26.0
FYM (35 t ha^{-1})	1,432	1,658	3,090	0.0
Ash from FYM	992	1,243	2,236	-27.6
PK minerals (no N)	1,130	1,294	2,424	-21.6
NPK (73 kg ha^{-1} N)	1,432	1,595	3,027	-2.0

Raw data is unavailable for statistical comparison, however, FYM yield just out matches NPK.

Table 12. Broadbalk mean cumulative wheat grain yields, t ha^{-1} at 85% dry matter 1852-2016 (i.e., 165 yr) on plots or treatments corresponding to the Broadbalk earthworm surveys.

	Plot 3/Nil	Plot 2.2/FYM	Plot 8/3NPK
Cumulative yield	21.38[a]	72.55[b]	74.63[b]
% change	-70.5	0.0	2.9

Data compiled from Rothamsted Research open access e-RA (2017 (http://www.era.rothamsted.ac.uk/metadata/broad/Broadbalk_YieldsJune2017.xlsx) [31]. Superscripts show ANOVA results with no statistical difference for FYM vs. NPK means.

Regarding yields, published data on Broadbalk show that FYM plots have consistently matched, or cumulatively out-yielded, even the best NPK chemical plots since inception, with grain yields conventionally presented as "85% DM" (dry matter) for wheat, oats and maize (data from Rothamsted Research 2012: figs. 1-2, tab. 1) [22]. This report also states for Barn Field that: "*A feature of the continuous roots and subsequent arable crops was the superiority of yield on soils given FYM, even where large amounts of N were applied in combination with the minerals*." Park Grass yields of dry hay (t/ha) in FYM, Nil and NPK plots corresponding to earthworm data are 8.8, 3.0 and 9.0 (Edwards & Lofty 1975: fig. 1) [12], (see also [22] tab. 2).

For Haughley farm, Widdowson (1987: tab. 9.3) [32] summarized the Land Economics Division of Cambridge University report from around 1981/82, corresponding to the earthworm survey period [15-16], showing average organic section yields higher by +7.7% (Table 13).

Table 13. Haughley farm yields (modified from Widdowson 1987: tab. 9.3 [32]/Hogg 2000: tab. 1.5 [33]) for 1981/2 corresponding to the earthworm survey period (£ = UK sterling).

	Organic	**Organic**	**Chemical**	**Chemical**	**Yield % change**
	Yield (t/ha)	**Gross (£/ha)**	**Yield (t/ha)**	**Gross (£/ha)**	**Org. v. Chem.**
Winter wheat	5.29	593	5.7	449	-7.2
Spring barley	5.04	500	4.24	322.7	+18.9
Oats	5.17	499	4.64	353.8	+11.4
Means	**5.2**	**£530.6**	**4.9**	**£375.2**	**+7.7%**

Gross margin difference for the organic v. chemical crops was £155/ha but this was less an extra 16% labour required (costing £23/ha for organic crops at that time), to give Net = £132 (+38%) profit. Raw data is unavailable for statistical comparison thus significance is uncertain.

Haughley wheat had shoots significantly increased by +13.9% and roots by +10.8% under organic management [15-17]. Moreover, Balfour (1977) [19] concluded that yields in terms of both plant growth and nutrient status from the Organic section remained consistently as high, and, despite chemically grown fodder having higher water content, the Organic dairy produced around +15% more milk than the Mixed over a 20-year period (this contrast was not due to a genetic factor for the separate Guernsey herds as the same bull was used). However, due to large interannual variations, overall none of the Haughley yield differences was considered significant during an earlier period from 1952-1966 [34].

Summary of the DOK trial results reported crop yields to be 20% lower in the organic systems after 21 years, although input of fertilizers and energy costs were reduced by -34% and -53%, pesticide input by -97%, plus the freely available biodiversity benefits were much higher [35].

Accompanying the earthworm data for the Philippines organic farms [17], summarized yields were higher by up to +80% (mean +39.1%) in tropical paddy rice and sugarcane, with soil moisture higher by +12.0% and soil organic carbon (SOC = humus) +64.9% higher than on neighbouring conventional farms.

Discussion

Soils and earthworms

Reduced humic soil organic matter – due to lower above and below ground crop yields and lack of recycling – as shown in the soil data tables above, with lower soil moisture that interactively results from reduced earthworm activity, are probable prime causes of earthworm declines. These losses are intensified by toxic poisoning by agrichemicals and over-cultivation of topsoil.

A 2014 survey of Rothamsted Broadbalk experiment earthworms [14] reported that annual application of 35 tha^{-1} of farmyard manure (FYM) after 171 years (this should be 131 years) increased the earthworm numbers by 469% and biomass by "1290%" (here recalculated as 1,700%) when compared to N fertilized soil plots. Rather, in my view what they found was that earthworms are actually depleted by -80 to -95% due to lack of organic amendments. This confirms a continued earthworm decline from earlier data provided by Morris (1922) [10] (depletion by -55%) and Edwards & Lofty (1975) [12] (depletion by -70%) from the same plots.

Edwards & Lofty (1982) [13] also had conclusions differing from this current reinterpretation of their rather contradictory data (herein using probably the most reliable of their stated results). Their conclusions were not supported by their data when it was stated that: "*There was a strong positive correlation (r = 0.9825) between amounts of inorganic N applied and populations of earthworms. Plots receiving both inorganic and organic N had the largest populations*". Rather, their findings showed how synthetic fertilizers actually reduced earthworms by more than -70% and it was FYM (Farm Yard Manure or "*% carbon*") that determined earthworms also at "*r = 0.983*" in their fig. 3. Adding inorganic fertilizer to organic FYM (plots 2.1 vs. 2.2) had negligible benefit for earthworms: their mean increases of +2.6% in numbers and +23.6% in biomass are both here calculated as not statistically significant (df = 6 ; t = 0.129; p = 0.901; NS for numbers; t =0.53613; p = 0.61; NS for biomass).

The earlier survey of Park Grass pasture at Rothamsted (Edwards & Lofty 1975) [12] also showed how addition of sulphate of ammonia had been devastating to the earthworms populations, in part by acidification with pH reduced <3.0 requiring lime remediation. The organic FYM plots had both higher earthworms and higher or equivalent yields. The Park Grass site had been in grass for several centuries and such old pastures would have been regularly manured, at least by grazing draught animals, deer and other stock. Thus earthworms, plants and invertebrates in the FYM plots may most closely resemble original biotic states compared to the transformations induced by subsequent synthetic agrichemical use. This supports

results determined at Haughley [15-16] that Organic arable worm populations are indeed closer to a permanent pasture's (but approximately halved), and that non-organic soils had greater depletion, on average by -35% in Mixed/compromise and Stockless/chemical fields.

Do long-term controls reasonably represent original states?

The answer to whether it is reasonable to suggest that organic arable treatments are more representative of historical states prior to synthetic chemicals and are thus proper "upper" controls is perhaps self-evident in view of the supposed prior histories of the experimental fields. Rothamsted is thought to have been farmland since Roman times in which case organic composts would likely have been used as Marcus Porcius Cato, 234 -149 BC described composting in his "*De Agri Cultura*" (Concerning Culture of the Fields) and Cais Plinius Secundus (AD 23-79), better known as Pliny the Elder, discussed various animal manures and recommended the use of many kinds of green manures [36]. The early English agriculturalist, Jethro Tull (1674-1740), was also a compost and ley-rotation advocate as was detailed by Loudon (1826) [37]. Thus, even if not exactly at original levels, it is probable that populations are closest to optimal as would be found in traditional farms since maintaining earthworm activity is a prime practical objective, or an unintended consequence, in organically managed soils. That said, soil organic carbon (SOC) data for Broadbalk is supposed to have undergone a rapid increase under FYM [38]. In my view this is incorrect, and more likely the judicious use of better prepared heritage composts and ley fallow would have given starting SOCs higher than those manifest at non-organic Rothamsted since 1843. Moreover, Lawes and Gilbert's design had both the FYM and the nil fertilizer plots as "standards" for comparison to the chemical fertilizer additions [26].

The Rothamsted originators, Lawes and Gilbert, had in the 1840s calculated that 14 tons per acre (= 35 tha^{-1}) 'average' FYM contained 200 Ib total N, or about equivalent to 224 kg ha^{-1} and thus Poulson (1996: fig. 1) [14] gives the content as 225 kg N ha^{-1} yr^{-1}. But other figures give fresh FYM containing 0.5% N and application of 10 tonnes providing about 50 kg [39], thus 35 t would supply just about 175 kg ha^{-1} by my reckoning. Confusingly, Edwards & Lofty (1982) [13] state: "*Annual fertilizer treatments were farmyard manure (48 and 96 kg N ha^{-1})*" suggesting an even lower rate especially since 96 kg is Rothamsted's "2N" that augmented the FYM (from 1885) in plot 2.1 since 1968 and was raised to "3N" or 144 kg N ha^{-1} since 2005. Sizmur et al. (2017) [14] had higher earthworm counts from plot 2.1 in spring 2014, albeit ANOVA of

Edwards & Lofty's 1979 [13] data from both 2.1 and 2.2 differed insignificantly thus were combined. Counts are possibly confounded or compromised in part by worm trans-migrations between plots only 6 m wide as, for example, several earthworm species reportedly migrate >20 m overnight [40]. Non-organic Broadbalk plot 2.1 using FYM plus synthetic fertilizers meshes with the Mixed sections of Haughley and of DOK mixed fertilizer trials that were both found to be almost as deleterious to earthworms, soils, and crop yields as fully chemical sections. This suggests that even Rothamsted's full FYM (plot 2.2 from 1843) is yet relatively inadequate with regards to wholly organic treatments. Earthworm biomass at 300 gm^{-2} in DOK organic sections [20] is three times Rothamsted's highest reports [14].

Comparison with other earthworm monitoring studies

Similar long-term earthworm study data are scarce and, where found, are unreliable for comparison due to different soils, seasons and sampling, although some long-term monitoring of populations does occur. In the USA, a 2015 review [41] show that conversion (reversion?) to organic production compares favourably to conventional in terms of healthy soil and yields, but unfortunately does not specifically address biodiversity. Moreover that review makes no mention at all of earthworms, not even from Rodale Institute's Farming Systems Trial (FST) operational since 1981. Thus the opportunity for survey of respective earthworm faunal populations in the six cited long-term trials in the USA is open for future research. In Europe there are other initiatives: E.g. in Holland (Netherlands Soil Monitoring Network) since 1997 in 6 yr cycles (Rutgers et al. 2009: fig. 3 has highest abundance at about 500 worms m-2 in pastures) [42], and several surveys in Germany are summarized by Jänsch et al. (2013: tab. 3) [43]. The average density and diversity across all sites in Germany from this latter report is here calculated as about 44 worms m^{-2} and just 3.8 species per site (maximum 5.3 ± 2.5 = ~8 species per site). Their case study of contaminated against uncontaminated grasslands (fig. 10) had approximate earthworm declines of -85% for abundance and -80% for species diversity, viz. from ten to two species on average. One Bavarian study (Bauchhenss 2005: figs. 16-17) [44] showed a slight upward trend in earthworm populations at 110 arable sites over 20 years due to better soil management (or a return to less deleterious organic management?), but populations were still about -74% below those in natural grasslands. Gaps in knowledge or deficiencies in assessment for EU soil monitoring were reported to include lack of data on earthworm communities and their roles [45], this despite a compilation report by Rutgers et al.

(2016: tab. 3) [46]. This latter report noted that earthworms were surprisingly under-represented taxa considering their key ecological importance and data yielded means, here recalculated, as 106.6 worms m^{-2} and just 4.1 species per site (maximum 10 + 0.95 percentile = ~11 species) for 8 countries. Often earthworms are omitted from most surveys and analyses.

As well as sparsity, these studies provide baseline data rather than allowing specific comparative analysis: For example, for the German samples [46] "*records from sites with anthropogenic impact other than physical soil cultivation measures (e.g., heavy metals, pollution, pesticide application, excessive nitrogen deposition) were not included.*" Thus much of this information is incomplete or irrelevant to the current study and differs from the author's experience where healthy soils may have much higher abundance and diversity. For example, roper eco-taxonomic survey yielded more than 20 megadrile species from disparate sites in Australia, Tasmania, Japan and Philippines [8, 17, 48] with 13 species found at Y Plas House in Machynlleth in just half a day [49] matching the earthworm diversity at one site in UK sampled during a 10-yr period (1990–2000) [50].

Supporting the insect and vertebrate decline trajectory, soils in some surveyed regions that are poorly managed, intensively cultivated, and/or chemically sprayed have earthworms severely depleted or completely annihilated from some fields in temperate and tropical climes [8, 17, 47-48]. Indeed, Rutgers et al. (2016: tab. 3) [46] reported zero worms in about 6% of all their surveys. Surveys of tropical palm oil plantations in Malaysia [51] have revealed low numbers, remarkably of only one species: Cosmopolitan South American *Pontoscolex corethrurus*. This ubiquitous interloper often dominates tropical soils in various stages of degradation [8, 17].

Agriculture – the primary factor of biotic declines

The present report clearly proves that, from its earliest days, chemical farming has been detrimental to soil life and certainly is responsible for killing the soil. For the recent German insect study [1], a plausible cause of the ~80% reduction in biomass of flying insects in just 27 years (1989-2016) was agricultural intensification with examples given by these authors as: "*pesticide usage, year-round tillage, increased use of fertilizers and frequency of agronomic measures*". They further note that this rate exceeds the estimated decline of -58% in global abundance of wild vertebrates over a 42-year period to 2012 [3], and was considerably more severe than the only comparable long term study on flying insect biomass from the UK [2].

This latter study of 30 years from 1973 to 2002 by Rothamsted Insect Survey (RIS) researchers used different methodology (suction tubes at 12.2 m height mainly designed to monitor flying aphids, rather than generalist malaise traps at ground level to 1 m). The RIS survey had a decline in only one of four stations but concluded the other three possibly already crashed due to earlier "*agricultural intensification*" from the 1950s as they all had much lower insect biomasses even than the declining site's final value. Moreover, aphids seem enhanced rather than depleted by chemical intensive agriculture as was found from Haughley organic farm data (Widdowson 1987: 70; Kowalski & Visser 1979; and by Birkhofer et al. 2008: fig. 5c) [32, 52, 21]. The latter Swiss report had approximately double the aphids in conventional chemical plots, despite use of insecticides. Likely reasons for higher pest levels are because organic plants are more resilient to attack or disease; pesticides differentially kill pest predators; plus the more rapidly reproducing insect pest species often rapidly develop resistance. This aphid problem was recognized but unsolved in Rothamsted's controversial GMO wheat trials. Heaton (2001) [53] similarly concurred that: "*Crop losses due to insects have increased by around 20 per cent since 1945 despite a 3,300 per cent increase in the amount of pesticides used*." This is restated as "*While insecticide use increased tenfold since the 1940s, crop losses to insects doubled*" (Soule & Piper, 1992: 46) [54]. See also discussion in Pimental (2005) [55].

Agronomic trials of reduced or minimum tillage/direct drill treatments often show earthworm increases: E.g. Briones & Schmidt (2017) [56] have numbers and biomass raised on average by 132% and 148%, respectively. However, as the total numbers are often much lower than of earthworms under proper organic production, then any conclusions are contextual. Moreover, these farm methods often rely upon excess herbicides, whereas organic minimum tillage practices use rotation, cover-crops, mulches and mechanical weeding. Certain "weeds" may also be encouraged for reasons of nitrogen-fixation, biodiversity aesthetics and as predator or pollinator reservoir refuges. Recent direct comparison determined that earthworms in organic treatments are two or three times the levels as found in agrichemical fields, far overriding any claims of reduced cultivation/herbicide treatment benefits (Crittenden et al. 2014) [57].

The growing failures of synthetic fertilizers

Despite best efforts for over 170 years, Rothamsted has been unable to demonstrate that synthetic fertilizers have any advantage over more natural organic fertilizer (FYM) in terms of yield, input costs, nor conservation of soil and its vital soil biota, such as earthworms.

Moreover, the organic fertilizers and management practices used at Rothamsted are inadequate compared to proper organic husbandry. For example, Sir Albert Howard (1947: 72) [58] was highly critical of their plot designs, weed control, poor heritage seed bank stocks, and lack of rotations (that were later implemented). And Lady Eve Balfour when she visited in 1948 (Gill 2010; 220-221) [59] said the FYM "composts" were substandard, hardly qualifying as such, thus any conclusions coming from Rothamsted about efficacy of proper organic composts were automatically invalid. Enhanced worm-processed vermicomposts are best [17].

Some other negative effect of synthetic fertilizer are on symbiotic mycorrhizae as summarized [60] with mycorrhizal abundance decreasing 15% under N fertilization and 32% under P fertilization. The self-perpetuating solution to this problem, ironically, is to supply more synthetic fertilizers and mineral supplements.

Other problems of chemical agriculture (as noted from early days at Rothamsted) are of soil acidity rate due to NO_3 from synthetic fertilizer use. Currently NO_x from farms in acid rain is more rapid and twice the total ocean acidification supposedly due to CO_2 from fossil fuels. A 2015 summary paper [61] show soil pH globally has acidified by an average of 0.26 in 20 years (about 100% change), while NOAA [62] has the pH of the surface ocean decreased by just 0.11 (which corresponds to approximately 30% increase in H) in the last 200 years. In China soils the effects are even more stark with an overall 0.5 pH reduction in the last 20 years, this is equivalent to a +216% change in acidity, about twice the global soil average [63]. This latter study shows that acidification has already lessened crop production by 30-50% in areas of China. The UK soils fare no better with 2.2 million tonnes of topsoil eroded annually and 17% of arable land with signs of erosion requiring greater use of grasslands such that around 18% of SOM present in 1980 has been lost by 1995 [64-65]. The situation is so dire that possibly as few as only another 100 harvests are left from UK soils [66-67], this supporting the UN's FAO summary that as little as 60 years of crops are possible with the current unsustainable intensive agricultural practices [68-69].

It is obvious that, even without the current information on earthworm decline, drastic changes are urgently needed. A starting point, often completely neglected, is implementing methods for restoration of soil fauna – in particular earthworms (that are particularly sensitive to pH) as "ecosystem engineers" to help rebuild healthy soils [7].

Significance of decreasing biodiversity

The method presented here of assessing biomass and biodiversity changes in soils degraded by unsound management relative to more appropriate soil conservation (viz. organic husbandry or mere FYM addition) allows previous data, such as from Rothamsted, to be re-evaluated and compared to more recently observed trends. Extrapolation of the German insect data [1] charts the trajectory of a rapid elimination of flying insect biomass in less than 30 years. Probably there will be stability with a new nadir at a much lower biomass, and this composed more of pest species – as was found by Morris (1927) [11] and recently by RIS [2] and as noted in a meta-analysis by Tuck et al. (2014) [14]. These latter authors claimed a conservative 30% increase biodiversity in organic fields, but omitted several relevant studies (e.g. some as cited herein). Moreover their conclusion that "*organic farming has large positive effects on biodiversity compared with conventional*" is more likely the opposite from their data, viz.: conventional farming depletes biodiversity by -23% (at least?) compared to organics.

Another meta-analysis by Bengtsson et al. (2005) [70] found on average, except for pest species, organisms were +50% more abundant in organic farming systems (or rather -33.3% lower in non-organic systems?). This was corroborated by Ewald et al. (2015) [71] who charted only slight decline in abundance in 42 years (1970-2011) in 26 invertebrate groups (including pests despite pesticide intensification) in agrichemical cereal fields in southern UK suggesting stability, albeit at a new and much lower biodiversity level. However, no non-cultivated nor organic controls were compared, biomass was unmeasured and, since they especially omitted earthworms, this latter work is therefore not particularly relevant to the current report. Most other studies consistently reveal earthworm and invertebrate declines, lower yields and soil degradation as manifest conclusively at Rothamsted and as compared to Haughley and DOK. This relates to UN's FAO prediction (noted above) that only another 60 harvests left at the current rates of intensive agricultural soil degradation, indicating no choice now but to change.

Practicability of organic restoration

Sir John Lawes in 1893 [72] made this definition; "*Practical agriculture consists in the artificial accumulation of certain constituents to be employed either as food for man or other animals, upon a space of ground incapable of supporting them in its natural state*."

Whether it is responsible to advocate reversion to more environmentally benign and sustainable organic farming as a practical solution to soil degradation whilst maintaining food supply has received some support from several key studies. Certainly the data presented above show the organic sites studied had equivalent or higher yields. The broad conversion to organic farming/permaculture as a priority may yet "*Feed Us All*" says Worldwatch Institute [73] whilst preserving biodiversity, sequestering carbon and saving both water and fossil energy. According to an UN summary study [74] agroecology led to an average crop yield gain of +79% and potential to store in soil humus 5.5 to 6 Gt of CO_2-equivalent per year by 2030.

Using various models, Muller et al. (2017) [75] indicated that it is possible for organic farming alone to supply all needs but would require more land unless food waste and arable land producing animal feed were both reduced. However, there appear several flaws in this study such as the yield gap cited as around 20%. Badgley et al. (2007: tab. 1, appendix 1) [76] presented summary result that yield ratio is 1.32 for organic plants and animals, on average for 293 reports, i.e., 32% higher than on conventional farms. Stanhill (1990) [34] found an average ratio from 205 comparisons of organic vs. conventional of 0.91 and concluded that "*(organic) yields within 10% of those obtained in conventional agriculture have been achieved without the use of (synthetic) agrochemicals*". This should be tempered with the higher mineral content of organic yields (or a higher water content of chemical yields) that is often around 10-20%. It was already known [77, 18, 78] and from Widdowson (1987: 146) [32] that the dry matter content of Haughley's organic section crops and fodder were about 15% higher than the chemical crops, further increasing meaningful yields. One of the latter references (Stonehouse 1981: 290) [78] also reported a 12-yr experiment (by Schuphan 1974) that found gross organic vegetable yields -24% down, but their dry-matter on average +23 % above the conventional chemical crops, which cancels out gross difference.

Nutritional value of organic produce is a further consideration as mineral, vitamin and water contents of some UK foods differ significantly over the period 1940-2002 (e.g. Thomas 2007) [80]. A 22-yr Swedish study proved organic wheat flour had higher ash content as a percentage of fresh weight with mean value 0.53 for conventional versus 0.67 for organic, i.e., organic grain had +26% extra minerals (0.47 vs. 0.33 or a true differences of ±14 percentage points) (Jorhem et al. 2013.: tab. 4) [79].

Furthermore, some crop comparisons are invalidated by just considering monoculture, whereas cyclical organic rotations offer both higher and more diverse yields from the same space of ground.

Does organic farming truly require more land?

The argument that organic farming would require more land has been partly answered above in the consideration of true yield values and soil degradation issues. Several other factors also require consideration [81]. Claims that organic farming has equivalent irrigation needs and soil erosion losses in the Muller et al. (2017) [75] report is perhaps also fallacious as organic farming and Permaculture are very much attuned to soil conservation, humus formation and topsoil restoration (e.g. Mollison 1988) [82] which is accompanied by better soil water relationships (often about +20% higher infiltration and storage, as shown in current data from Rothamsted's Broadbalk soils and the Haughley soil data above). Interestingly, (Russell 1940) [83] reported Broadbalk's FYM plot had less run-off compared to the adjacent Nil plot: From 1903-1914 they drained on ten against 232 days, respectively, showing not only that water is stored (due mainly to earthworm activities), but also how soil erosion and nutrient leaching may be almost entirely reduced with proper management.

It is important to realize that the dominant agricultural intensification system prevailing in the last century has already been associated with a 20-50% loss of soil fertility by erosion (as noted below) and this is coupled with the dramatic and rapid annihilation of both vertebrates and invertebrates as the main topic in this current report. Evidence shows a need for more balanced management to protect our finite soil ecosystem. UN's severe criticism of chemicals for damaging health and the environment yet not providing any improved crop protection for the last 40 years (UN 2017 original; Guardian 2017 summary) [84-85] . This UN report also noted that in China 20% of arable land is rendered unfarmable due to chemical pollution, 33% of China's surface water is polluted and >80% of its aquifer well water is unfit to drink or bathe in (Wong 2014; Zhou & Zhang 2016; USCC 2017: 16) [86-88]. In India the situation may be worse with 50% land degraded in some way, almost all water polluted and the annual direct cost of land loss put at \$8.5 billion per year (Bhattacharyya et al. 2015) [89]. These reports point to intensive agriculture itself increasingly requiring more land in order to provide the same yields whilst, in contrast, organic production simultaneously conserves nature on site.

Earthworm benefits

While not considering organic farming *per se*, a recent meta-analysis [90] confirmed crop yield increases of +25% corresponding to presence of earthworms which, as the current study shows, are adversely depleted by agricultural intensification. This supports research over a century earlier by Wollny (1890: 381) [91] where earthworms in soils led to a marked increase of cereal grain (by +35-50%) and straw (by +40%). Inexplicably, earthworm benefits have not been much promoted and are still mostly neglected. Yet it is impossible to replace or artificially engineer all the beneficial processes and services freely provided by earthworms [6-7]. In just one instance, their burrows in SOM-enriched pastures may extend up to 9,000 km ha^{-1} [92] to allow ingress of air and water and provide living space for other soil organisms, thereby enhancing natural soil nutrient mineralization in synchrony and *in situ* in the root zone.

Economic considerations

It would be remiss to omit some economic evaluation. An updated 2017 review [93] estimates the value of free ecological services with a median value of $135 trillion per year that is almost double the global economic GDP of around $75 trillion [94]. Thus Ecology appears arguably more important than Economy. Ecological losses from land use changes (mainly due to industrial-chemical agriculture) [93] are estimated at around $4 trillion per year which is about double the global combined Agriculture, Forestry and Fisheries contribution of $1.9 trillion [95]. A 2013 cost-benefit analysis estimated that environmental and human health damages caused by agricultural N pollution in the EU exceeded their economic benefits of increased agricultural production by about fourfold [96], supporting Rockström et al.'s (2009) [5] call for reduction in synthetic N fertilizers by 25%. A recent UK report further shows chemical food incurs hidden costs that double the real price, mainly due to pollution and healthcare [97] making organic restoration an even more appealing and sensible option in terms of ecology, health and economy.

Conclusions

"*We must turn all our* resources *to repairing the natural world*" (Dr Bill Mollison, 1928-2016).

Critical biotic declines are linked to widespread intensive agrichemical practices that use simplistic chemical synthetics in non-laboratory settings as a replacement for natural processes. As stated in the laws of thermodynamics, it takes energy to maintain any system in a complex, ordered and sustainable state, and proportionately it takes twice the effort to double a vital resource (e.g., 50 to 100 is +100%) than to halve it (e.g., 100 to 50 is -50%). Rothamsted's long-term trials clearly demonstrate that supply of organic FYM fertilizer (SOM) is most crucial to preservation of earthworms which otherwise decline by -60 to -100% and differing levels of synthetic fertilizers provide little if any overall benefit. Higher levels of abundance and biodiversity are attainable when organic husbandry is fully implemented. Cases using mixed (i.e., combination of organic and chemical) compromises were demonstrated at Haughley and in the Swiss DOK trials to be just as deleterious. This was not conclusively shown at Rothamsted, but neither were full organic methods meaningfully applied or tested there.

Thus is it concluded that cascading soil fauna depletion occurs when woodland is cleared for pasture, when pasture is cultivated for crops, when synthetic fertilizers replaced organics, especially after WW1, and when excessive toxic and systemic biocides were introduced, especially following WW2. Continued catastrophic trajectory for earthworms – the builders of fertile topsoils and SOM upon which most life on Earth ultimately depends – seems as likely as for insects and most other organisms. Possible solutions to restore biotic abundance and curtail loss of biodiversity are readopting or re-investing in more natural farming using organic fertilizers and avoiding chemical poisons. Concomitant with a shift by farmers and consumers, governments may need to reallocate funding from agri-chemistry that continues to seek stop-gap solutions to problems often caused by chemical toxins, and to raise support for practical, applied agro-ecology and sustainable Permaculture for efficient and flexible natural designs. It is timely to restore earthworms in order to rebuild topsoil humus thus allowing organic transition farming to rapidly reach its full capacity and to go "Beyond Organic" [98].

The findings of this report support the conclusions that e Excess N in agriculture leads to soil acidification, accelerates soil-organic-matter (SOM or humus) turnover and alters and/or disrupts soil faunal and microfloral communities [99]. On a positive note, an incontrovertible loss of regional plant biodiversity due to atmospheric and soil nitrogen pollution reversed in just 20 yrs after synthetic fertilizer application ceased on Rothamsted plots [100]. Although as

yet unobserved in the wider landscape, such restoration, if pertaining to animals too, indicates a solution to insect and earthworm declines.

Further long-term monitoring is required of well-managed organic farms that likely retain heritage soil faunas, as an appropriate measure of the realistic status of healthy earthworm populations, in contrast to more intensified non-organic/agrichemical sites. Currently only limited information is available, and search of Global Biodiversity Information Facility (https://www.gbif.org/search?q=earthworms%20organic Dec., 2017) yields one report, highlighting a deficit in our knowledge of agroecosystem functioning and basic soil ecology and the need to re-evaluate .

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References

1. Hallmann, C.A.; Sorg M.; Jongejans, E.; Siepel, H.; Hofland, N.; Schwan, H.; et al. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLoS ONE* **2017,** *12(10)*, e0185809, DOI: doi.org/10.1371/journal.pone.0185809.

2. Shortall, C.R.; Moore, A.; Smith, E.; Hall, M.J.; Woiwod, I.P.; Harrington, R. Long-term changes in the abundance of flying insects. *Insect Conserv. Diver.* **2009**, *2(4)*, 251–260, Available online: http://onlinelibrary.wiley.com/doi/10.1111/j.1752-4598.2009.00062.x/full .

3. Ceballos, G.; Ehrlich, P.R.; Dirzo, R. Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. PNAS, **2017**, p. 201704949, DOI: 10.1073/pnas.1704949114. Available online: http://www.pnas.org/content/114/30/E6089.full.pdf .

4. WWF International. Living Planet Report 2016: Risk and resilience in a new era. Gland, Switzerland. 2016;. Available online: http://wwf.panda.org/about_our_earth/all_publications/lpr_2016/ .

5. Rockström J, Steffen W, Noone K, Persson Å, Chapin III FS, Lambin EF, et al. A safe operating space for humanity. Nature. 2009; 461:472–475. doi:10.1038/461472a. Available from: http://steadystate.org/wp-content/uploads/2009/12/Rockstrom_Nature_Boundaries.pdf.

6. Darwin CR. The formation of vegetable mould through the action of worms, with observation on their habits. London: Murray; 1881.

7. Lee KE. Earthworms: Their ecology and relationships with soils and land use. Sydney: Academic Press. 1985.

8. Blakemore RJ. Cosmopolitan earthworms – an eco-taxonomic guide to the peregrine species of the world. 6th ed. Yokohama: VermEcology.pp. 1,300; 2016.

9. Tuck SL, Winqvist C, Mota F, Ahnström J, Turnbull LA, Bengtsson J. Land-use intensity and the effects of organic farming on biodiversity: a hierarchical meta-analysis. J. Appl Ecol. 2014; 51(3): 746–755. https://doi.org/10.1111/1365-2664.12219. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4299503/.

10. Morris HM. Insect and other invertebrate fauna of arable land at Rothamsted. Ann Appl Biol. 1922;9:282–305.

11. Morris HM. The insect and other invertebrate fauna of arable land at Rothamsted. Part II. Ann appl Biol. 1927;14:442-464.

12. Edwards CA, Lofty JR. The invertebrate fauna of the Park Grass Plots. I. Soil fauna. Rothamsted Exp Stn Rep 1974 (Part 2). 1975; pp. 133–154. Available from: http://www.era.rothamsted.ac.uk/eradoc/OCR/ResReport1974p2-135-156.

13. Edwards CA, Lofty JR. Nitrogenous fertilizers and earthworms populations in agricultural soils. Soil Biol Biochem. 1982;147:515-521. doi:10.1016/0038-0717(82)90112-2. Available from: https://www.sciencedirect.com/science/article/pii/0038071782901122.

14. Sizmur T, Martin E, Wagner K, Parmenteir E, Watts C, Whitmore AP. Milled cereal straw accelerates earthworm (*Lumbricus terrestris*) growth more than selected organic amendments. Appl Soil Ecol. 2017; 113:166-177. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5391807/.

15. Blakemore RJ. B.Sc. (Hons.) Dissertation. Ecology of earthworms under different fertilizer regimes in agriculture. Westminster Uni., 801/1/22. 1981 pp 93.

16. Blakemore RJ. Ecology of earthworms under the "Haughley Experiment" of organic and conventional management regimes. Biol Agric Hortic. 2000;18(2):141-159. Available from: http://www.annelida.net/earthworm/Haughley/Haughley.doc.

17. Blakemore RJ. *Veni, Vidi, Vermi* – II. Earthworms in organic fields restore SOM & H_2O and fix CO_2. VermEcology Occasional Papers. 2016;2(2):1-26. DOI: 10.13140/RG.2.2.11022.97608. Available from: https://veop.wordpress.com/2016/09/01/volume-2-2/.

18. Balfour EB. (with Milton RF). The living soil and the Haughley experiment. 2nd ed. London: Faber & Faber; 1975. (http://organiccollege.com/dl/file.php/1/the-living-soil.pdf).

19. Balfour EB. Towards a sustainable agriculture – The Living Soil. Address to an International Federation of Organic Agricultural Movements (IFOAM) conference in Switzerland; 1977. Available from: http://www.soilandhealth.org/01aglibrary/010116Balfourspeech.html.

20. Pfiffner L, Mäder P. Effects of Biodynamic, Organic and Conventional Production Systems on Earthworm Populations. Biological Agriculture and Horticulture 1997; 15: 3-10. https://www.researchgate.net/publication/254214562_Effects_of_Biodynamic_Organic_and_Conventional_Production_Systems_on_Earthworm_Populations.

21. Birkhofer, K, Bezemer TM, Bloem J, Bonkowski M, Christensen S, Dubois D, et al. Long-term organic farming fosters below and aboveground biota: Implications for soil quality, biological control and productivity. Soil Biol Biochem. 2008;40:2297-2308. DOI: 10.1016/*j*.soilbio.2008.05.007.

22. Rothamsted Research. Guide to the Classical and other Long-term Experiments, Datasets and Sample Archive. Lawes Agricultural Trust (2006, reprinted 2012). 2012. pp. 51. Available from: https://www.rothamsted.ac.uk/sites/default/files/LongTermExperiments_PDF.pdf.

23. Franklin JF. Importance and justification *of* long-term studies in ecology. In: Likens GE. ed. Long-term studies in ecology, pp. 3—19. New York: Springer-Verlag; 1989. pp. 3–19.

24. Poulson PR. The Rothamsted long-term experiments: Are they still relevant? Can J Plant Sci. 1996;76:559–571. Available from: www.nrcresearchpress.com/doi/pdf/10.4141/cjps96-103.

25. Balfour EB. The living soil: Evidence of the importance to human health of soil vitality, with special reference to post-war planning. 7th ed. London: Faber and Faber Ltd; 1947.

26. Johnston AE, Garner HV. Rothamsted Experimental Station Report For 1968 - Part 2. 1969;., pp 12–25. - DOI: https://doi.org/10.23637/ERADOC-1-34916. Available from: http://www.era.rothamsted.ac.uk/eradoc/OCR/ResReport1968p2-12-25.

27. Clark IM, Buchkina N, Jhurreea D, Goulding KW, Hirsch PR. Impacts of nitrogen application rates on the activity and diversity of denitrifying bacteria in the Broadbalk Wheat Experiment. Philos Trans R Soc Lond B Biol Sci. 2012 May 5;367(1593):1235-44. doi: 10.1098/rstb.2011.0314. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3306624/#RSTB20110314C13.

28. Martindale W. The Rothamsted long term agricultural experiments. 2001 Available from: https://waynemartindale.files.wordpress.com/2017/04/oecdfellowship1004.pdf.

29. Jones KC, Johnston AE. Cadmium in cereal grain and herbage from long-term experimental plots at Rothamsted, UK. Environ Pollut. 1989;57(3):199-216. DOI: 10.1016/0269-7491(89)90012-2.

30. Addiscott TM. Nitrate, agriculture, and the environment. Wallingford, UK: CABI Publishing pp. 304. 2005. Available from: https://www.wou.edu/las/physci/taylor/Monmouth_Hydrogeology/Addiscott_2005_Ch1_nitrogen_overview.pdf.

31. Rothamsted Research. Open access e-RA report. Dec 2017. Available from: http://www.era.rothamsted.ac.uk/metadata/broad/Broadbalk_YieldsJune2017.xlsx.

32. Widdowson RW. Towards holistic agriculture: A scientific approach. Pergammon. 1987.

33. Hogg D. Technological change in agriculture: Locking in to genetic uniformity. New York: St. Martin's Press; 2000. pp. 296.

34. Stanhill G. The comparative productivity of organic agriculture. Agric Ecosys Environ. 1990; 30:1-26. https://doi.org/10.1016/0167-8809(90)90179-H.

35. Mäder P, Fließbach A, Dubois D, Gunst L, Fried P, Niggli U. Soil fertility and biodiversity in organic farming. Science. 2002;296:1694-1697. Available from: http://www.ask-force.org/web/Organic/Maeder-Organicfarming-2002.pdf.

36. Korcak RF. Early Roots of the Organic Movement: A Plant Nutrition Perspective. Hort Technology. 1992;2:263–267. Available from: http://horttech.ashspublications.org/content/2/2/263.full.pdf.

37. Loudon JC. An encyclopædia of agriculture. Longmans, London ; 1826. Available from: https://www.biodiversitylibrary.org/bibliography/21875#/summary.

[orphan] Rothamsted Research. Open access e-RA report. Dec 2017. Available from: https://www.rothamsted.ac.uk/sites/default/files/LongTermExperiments_PDF.pdf figs. 1-2.

38. Rothamsted Research. Open access e-RA report. Dec 2017. Available from: http://www.era.rothamsted.ac.uk/Broadbalk/bbk_open_access.

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.623.716&rep=rep1&type=pdf .

39. Researchgate.net article. December 2017. Available from: www.researchgate.net/post/What_are_the_typical_N_P_and_K_values_of_farmyard_manure.

40. Blakemore RJ. The diversity of exotic earthworms in Australia – a status report. In: Ponder W. Lunney D. eds. Proceedings of "The Other 99%". Transactions of the Royal Zoological Society of NSW, 1999. pp 182-187. Available from: http://biocollections.org/pub/worms/docs/Blakemore-eworms-Diversity-of-exotics.html

41. Delate K, Cambardella C, Chase C, Turnbull R. A review of long-term organic comparison trials in the U.S. Sustain. Agric. Res. 2015;4:5–14. Available from: http://www.ccsenet.org/journal/index.php/sar/article/view/50095.

42. Rutgers M, Schouten A, Bloem J, Van Eekeren N, De Goede R, Jagersop Akkerhuis G, et al. Biological measurements in a nationwide soil monitoring network. Eur J Soil Sci. 2009; 60:820–32. Available from: https://www.researchgate.net/publication/224946248_Biological_measurements_in_a_nationwide_soil_monitoring_network.

43. Jänsch S, Steffens L, Höfer H, Horak F, Roß-Nickoll M, Russell D, et al. State of knowledge of earthworm communities in German soils as a basis for biological soil quality. Soil Org. 2013;85(3): 215-233. Available from: http://www.senckenberg.de/files/content/forschung/publikationen/soilorganisms/volume_85_3/07_artikel_stephan_jansch_et_al.pdf.

44. Bauchhenß J. Zeitliche veränderungen der regenwurm-taxozönosen auf grünland und auf ackerflachen. In: 20 Jahre Bodendauerbeobachtung in Bayern. Zwischenbilanz der wichtigsten Ergebnisse 1985-2005. LfL-Schriftenreihe 8/2005. pp. 41-48. Available from: https://www.lfl.bayern.de/mam/cms07/publikationen/daten/schriftenreihe/p_19778.pdf .

45. Van Leeuwen JP, Saby N, Jones A, Louwagie G, Micheli E. Rutgers M, et al. Gap assessment in current soil monitoring networks across Europe for measuring soil functions. Environ. Res. Lett. 2007; 12:124007. https://doi.org/10.1088/1748-9326/aa9c5c. Available from: http://iopscience.iop.org/article/10.1088/1748-9326/aa9c5c/pdf.

46. Rutgers M, Orgiazzi A, Gardi C, Römbke J, Jänsch S, Keith AM, et al. Mapping earthworm communities in Europe. Appl. Soil Ecol. 2016; 97:98 DOI: 10.1016/j.apsoil.2015.08.015.

47. Blakemore RJ. Earthworms of south-east Queensland and their agronomic potential in brigalow soils. Ph.D. Thesis, University of Queensland. 1994. pp. 605. DOI: 10.14264/uql.2017.476. Available from: https://espace.library.uq.edu.au/view/UQ:366290/THE8652.pdf.

48. Blakemore RJ. *Veni, Vidi, Vermi* – I. On the contribution of Darwin's 'humble earthworm' to soil health, pollution-free primary production, organic 'waste' management & atmospheric carbon capture for a safe and sustainable global climate. VermEcology Occasional Papers. 2016;2(1):1-34. Available from: http://orgprints.org/31188/3/VVV%20part-I.pdf.

49. Blakemore RJ. Miscellaneous earthworm types in the Natural History Museum, London (Annelida: Oligochaeta: Megadrilacea: Eudrilidae, Lumbricidae, Megascolecidae, Moniligastridae, Octochaetidae). Opusc Zool Inst Zoosyst Oecol Univ Bp. 2014;45(2):199-155. Available from: http://opuscula.elte.hu/PDF/Tomus45_2/2_Op_Blakemore_London_Museum_worms.pdf.

50. Hutcheon A, Iles DR Kendall DA. Earthworm populations in conventional and integrated farming systems in the LIFE Project (SW England) in 1990–2000. Ann Appl Biol. 2001; 139(3): 361-372. DOI: 10.1111/j.1744-7348.2001.tb00150.x.

51. Sabrina DT, Hanafi MM, Nor Azwady AA, Mahmud TMM. Earthworm populations and cast properties in the soils of oil palm plantations. MJSS. 2009;13:29–42. Available from: http://www.msss.com.my/mjss/Full%20Text/Vol%2013/sabrina.pdf.

52. Kowalski R, Visser PE. Nitrogen in a crop-pest interaction: Cereal aphids. In: Lee JA, McNeil S, Rorison LH. editors. Nitrogen as an Ecological Parameter. Oxford: Blackwell Scientific Press. 1979; pp. 283-300.

53. Heaton S. Organic Farming, Food Quality and Human Health. Soil Association report. Bristol, UK; 2001. pp. 87. Available online: https://www.soilassociation.org/media/4920/policy_report_2001_organic_farming_food_quality_human_health.pdf.

54. Soule J, Piper J. Farming in Nature's image. Washington, DC: Island Press; 1992.

55. Pimentel, D. (2005) Environmental and economic costs of the application of pesticides primarily in the United States. Environment, Development and Sustainability, 7, 229-252. doi10.1007/s10668-005-7314-2.

56. Briones MJI, Schmidt O. Conventional tillage decreases the abundance and biomass of earthworms and alters their community structure in a global meta-analysis. Global Change Biology, 2017; DOI: 10.1111/gcb.13744.

57. Crittenden SJ, Eswaramurthy T, de-Goede RGM, Brussaard L, Pulleman MM. Effect of tillage on earthworms over short- and medium-term in conventional and organic farming. Appl. Soil Ecol. 2014;83:140–148. DOI: 10.1016/j.apsoil.2014.03.001. Available from: http://snowmannetwork.com/wp-content/uploads/SN03-14-18_Crittenden-et-al-2014_Applied-Soil-Ecology.pdf.

58. Howard A. An Agricultural testament. London: Oxford University Press; 1947. Available from: http://krishikosh.egranth.ac.in/bitstream/1/2026951/1/BPT3823.pdf.

59. Gill, E. Lady Eve Balfour and the British organic food and farming movement. Ph.D. Thesis, Department of History & Welsh History, Aberystwyth University. November 2010. Available from: http://ladyevebalfour.org/down/Lady-Eve-Balfour-by-Erin-Gill.pdf.

60. Treseder KK. A meta-analysis of mycorrhizal responses to nitrogen, phosphorus, and atmospheric CO2 in field studies. New Phytol. 2004; 164:347–355. Available from: - https://escholarship.org/content/qt8783k14r/qt8783k14r.pdf.

61. Tian D, Niu S. A global analysis of soil acidification caused by nitrogen addition. Environment Research Letters. 2015;10(2). Available from: http://iopscience.iop.org/article/10.1088/1748-9326/10/2/024019.

64. UK Government Reports. UK Soil Degradation. July 2006 Number 265. Available from: http://www.parliament.uk/documents/post/postpn265.pdf.

62. NOAA. A primer on pH. 2017. Available from: https://www.pmel.noaa.gov/co2/story/A+primer+on+pH.

63. Gilbert N. Acid soil threatens Chinese farms. Nature; 1989; published online. doi:10.1038/news.2010.67. Available from: http://www.nature.com/news/2010/100211/full/news.2010.67.html.

64. UK Government Reports. UK Soil Degradation. July 2006 Number 265. Available from: http://www.parliament.uk/documents/post/postpn265.pdf.

65. Research. Open access e-RA report. Dec 2017. Available from: https://www.rothamsted.ac.uk/sites/default/files/soil-health.pdf.

66. Edmondson JL, Davies ZG, Gaston KJ, Leake JR. *Urban cultivation in allotments maintains soil qualities adversely affected by conventional agriculture*. J Appl Ecol. 2014; DOI: 10.1111/1365-2664.12254. Available from; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4301088/.

67. Withnall A. Independent Newspaper article. 2014. Available from: - http://www.independent.co.uk/news/uk/home-news/britain-facing-agricultural-crisis-as-scientists-warn-there-are-only-100-harvests-left-in-our-farm-9806353.html.

68. Crawford J. What if the World's soil runs out? Time: World Economic Forum. 14 Dec 2012. Available from: http://world.time.com/2012/12/14/what-if-the-worlds-soil-runs-out/.

69. Arsenault C. Only 60 years of farming left if soil degradation continues. Scientific American. 2014. Available from: https://www.scientificamerican.com/article/only-60-years-of-farming-left-if-soil-degradation-continues/.

70. Bengtsson J, Ahnstrom J, Weibull, AC. The effects of organic agriculture on biodiversity and abundance: A meta-analysis. J Appl Ecol. 2015,42:261-269. http://dx.doi.org/10.1111/j.1365-2664.2005.01005.x. Available from: http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2664.2005.01005.x/pdf .

71. Ewald JA, Wheatley CJ, Aebischer NJ, Moreby SJ, Duffield SJ, Crick HQ, et al. Influences of extreme weather, climate and pesticide use on invertebrates in cereal fields over 42 years. Global Change Biology. 2015;21(11):3931–3950. pmid:26149473.

72. Lawes JB, Gilbert JH. The Rothamsted memoirs on agricultural chemistry and physiology. Vol. I: Reports of field experiments, &c, &c. London: Clowes & Sons; 1893. Available from: https://archive.org/stream/rothamstedmemoi02lawegoog/rothamstedmemoi02lawegoog_djvu.pdf.

73. Worldwatch Institute. Can Organic Farming Feed Us All? 2006;. Available from: http://www.worldwatch.org/node/4060 .

74. UN Report 2010. Available from: http://www2.ohchr.org/english/issues/food/docs/A-HRC-16-49.pdf .

75. Muller A, Schader C, Scialabba, NE-H, Brüggemann J, Isensee A, Erb K. et al. Strategies for feeding the world more sustainably with organic agriculture. Nature communications. 2017;8: 1290. DOI: 10.1038/s41467-017-01410-w. Available from: https://www.nature.com/articles/s41467-017-01410-w .

76. Badgley C, Moghtader J, Quintero E, Zakem E, Chappell MJ, Aviles-Vazquez, K, et al. Organic agriculture and the global food supply. Renew Agr Food Syst. 2007; 22(2):86–108. doi:10.1017/S1742170507001640.

77. Mayall S. An English organic farm. Haughley: Soil Association. 1965. Available from: https://www.pimhill.com/assets/Uploads/English-Organic-Farm.pdf.

78. Stonehouse B. Biological husbandry: A scientific approach to organic farming. London: Butterworths; 1981.

79. Jorhem L, Sundström B, Engman J. Trends in Cadmium and Certain. Other Metal in Swedish Household. Wheat and Rye Flours 1983-2009: NATIONAL FOOD. AGENCY, Sweden. LIVSMEDELS. VERKET. Rapport 16; 2013. Available from: https://www.livsmedelsverket.se/globalassets/rapporter/2013/2013-national-food-agency-16---trends-in-cadmium-and-certain-other-metal-in-swedish-household-wheat-and-rye-flours-1983-2009.pdf.

80. Thomas D. The mineral depletion of foods available to us as a nation (*1940-2002*)--a review of the 6th Edition of McCance & Widdowson. Nutr Health. 2007;19(1-2):21-55. Available from: http://www.mineralresourcesint.co.uk/pdf/Mineral_Depletion_of_Foods_1940_2002.pdf .

81. Johnson N. Do industrial agricultural methods actually yield more food per acre than organic ones? 2015. grist.org commentary. Oct 14, 2015. Available from: http://grist.org/food/do-industrial-agricultural-methods-actually-yield-more-food-per-acre-than-organic-ones/.

82. Mollison, B. Permaculture: A designers' manual. Australia: Tagari Publications; 1988.

83. Russell EJ. A student’s book on soils and manures. 3rd edn. Cambridge: University Press; 1940.

84. UN Report Dec 2017. Available from: https://documents-dds-ny.un.org/doc/UNDOC/GEN/G17/017/85/PDF/G1701785.pdf?OpenElement.

85. Guardian newspaper. 7 Mar 2017. UN experts denounce myth that pesticides are necessary to feed the world. Available from: https://www.theguardian.com/environment/2017/mar/07/un-experts-denounce-myth-pesticides-are-necessary-to-feed-the-world.

86. Wong E. One-fifth of China’s farmland is polluted, state study Finds. The New York Times. 17 April 2014. Available from: https://www.nytimes.com/2014/04/18/world/asia/one-fifth-of-chinas-farmland-is-polluted-state-report-finds.html.

87. Zhou C, Zhang Y. China's tainted soil initiative lacks pay plan. Caixinglobal. 2016;. Available from: https://www.caixinglobal.com/2016-06-08/101011627.html.

88. USCC Report. 14 Feb 2017. Available from: https://www.uscc.gov/sites/default/files/Research/The%2013th%20Five-Year%20Plan_Final_2.14.17_Updated%20%28002%29.pdf.

89. Bhattacharyya R, Ghosh BN, Mishra PK, Mandal B, Rao CS, Sarkar D,et al. Soil degradation in India: Challenges and potential solutions. Sustainability. 2015;7:3528-3570. doi:10.3390/su7043528. Available from: https://pdfs.semanticscholar.org/bfbd/dd0cc41fa8e6d2a9d64830750aa4d36e7e8f.pdf.

90. van Groenigen JW, Lubbers IM, Vos HMJ, Brown GG, De Deyn GB, van Groenigen KJ (2014) Earthworms increase plant production: a meta-analysis. Sci Rep. 2014; 4:6365. DOI: 10.1038/srep06365. Available from: https://www.researchgate.net/publication/265647813_Earthworms_increase_plant_production_A_meta-analysis.

91. Wollny E. (1890: Forschungen auf der Gebiet der Agrikultur-Physik. Heidelberg: Carl Winter´s Universitätsbuchhandlung. Bd. 13, s. 381 pp. 540. 1890.

92. Kretzschmar A. Description des galeries de vers de terre et variations saisonnières des réseaux (observations en conditions naturelles). Rev Ecol Biol Sol. 1982;19: 579–591.

93. Costanza R, Groot RS de, Sutton P, Ploeg, S van der, Anderson SJ. *et al*. *Changes in the global value of ecosystem services*. Global environmental change : human and policy dimensions. 2014;26:52-158. https://doi.org/10.1016/j.gloenvcha.2014.04.002. Available from: http://www.sciencedirect.com/science/article/pii/S0959378014000685.

94. Fitzpatrick I. Valuing nature and the hidden costs of biodiversity loss. 2017. Available from: http://sustainablefoodtrust.org/articles/valuing-nature-and-the-hidden-costs-of-biodiversity-loss/?utm_source=SFT+Newsletter&utm_campaign=5117bb6a15-

Newsletter_26_10_2017&utm_medium=email&utm_term=0_bf20bccf24-5117bb6a15-105104433.

95. UN-FAO Report. 2015. Available from: www.fao.org/fileadmin/templates/ess/documents/GDP/IND_NewsRelease_EN__27Apr2015_.pdf.

96. Van Grinsven HJ, Holland M, Jacobsen BH, Klimont Z, Sutton MA, Jaap Willems W, et al. Costs and benefits of nitrogen for Europe and implications for mitigation. Environ Sci Technol. 2013;47(8):3571-9. doi:10.1021/es303804g. Available from: http://pubs.acs.org/doi/abs/10.1021/es303804g.

97. Fitzpatrick I, Young R, Perry M, Rose E. The hidden cost of UK food: Summary report November 2017. 2017; pp 20. Available from: http://sustainablefoodtrust.org/wp-content/uploads/2013/04/Summary-PDF-9-Nov-for-online.pdf.

98. Reganold JP, Wachter JM. Organic agriculture in the twenty-first century. Nature plants 2016;2:15221. doi:10.1038/nplants.2015.221. Available online: https://www.nature.com/articles/nplants2015221.

99. Cheeke TE, Coleman C, Wall DH. 2013. Microbial Ecology in Sustainable Agroecosystems. CRC Press.

100. Storkey J, Macdonald AJ, Poulton PR, Scott T, et al. 2015. Grassland biodiversity bounces back from long-term nitrogen addition. Nature;528:401-404. doi:10.1038/nature16444.

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